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RIVER RESEARCH AND APPLICATIONS

River. Res. Applic. **25**: 607–625 (2009)

Published online 17 February 2009 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/rra.1243

SCIENTIFIC DESIGN STRATEGY FOR PROMOTING SUSTAINABLE SEDIMENT MANAGEMENT: THE CASE OF THE MAGRA RIVER (CENTRAL-NORTHERN ITALY)

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ABSTRACT

The Magra River (Central-Northern Italy) and its main tributary, the Vara River, have been heavily affected by sediment mining and other human disturbances that have caused channel incision and a series of associated negative environmental effects. As a consequence, the Basin Authority of Magra River has recently implemented a new river management policy based on an understanding and analysis of geomorphic processes. This paper describes and illustrates a methodology that defines a scientifically-based strategy for promoting future sustainable management of sediment and channel processes within this catchment. The methodology is based on a diagnosis which incorporates retrospective analyses of channel geometry, causes of changes and hydraulic sediment budgets to evaluate potential sediment transport. All these data are summarized using a multi-criteria approach to develop an overall design strategy for medium-term (i.e. some decades) bed sediment management. A practical methodology to identify potential sources of sediment at the catchment scale and to promote sediment delivery is also described. Finally, a 'map of strategies for sediment management' is presented, which synthesises all the aspects studied (morphological evolution, sediment budgets and considerations of potential sediment recharge). Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: channel changes; sustainable management; sediment budget; erodible river corridor; sediment recharge; Magra River

Received 11 December 2008; Accepted 17 December 2008

INTRODUCTION

Sediment transport, bank erosion and associated channel mobility represent key physical processes, and their understanding is of crucial importance for defining river restoration and management strategies (Piégay *et al*., 2005; Habersack and Piégay, 2008).

In Italy, as in many other parts of Europe, most alluvial channels have experienced severe incision and bedload deficit, mainly due to a series of human factors (Surian and Rinaldi, 2003; Surian *et al*., 2009b). This evolution has led to the need for sustainable sediment management, notably to promoting bedload supply and recharge, bank erosion preservation and restoration, but also to undertake measures for mitigating impacts of channel incision (Bravard *et al*., 1999; Habersack and Piégay, 2008; Liébault *et al*., 2008).

Sediment exploitation within alluvial channels is frequently the main cause of sediment deficit and channel incision. Common practices carried out by river management agencies demonstrate that sediment management has rarely been based upon scientific knowledge (Rinaldi *et al*., 2005). Even in countries where sediment mining has been formally prohibited (e.g. France, Italy), permissions are often still granted, motivated by increasing channel capacities for flood water and the prevention of erosion of undercut concave banks positioned against channel bars. For these reasons, a different approach to sediment management is desirable, incorporating: (i) knowledge and management of sediments at the basin scale; (ii) a wider application of available scientific knowledge, particularly of fluvial geomorphology and hydraulics.

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Sediment mining, combined with other human disturbances, has heavily affected the alluvial channels in the Magra River catchment (Central-Northern Italy) in recent decades, providing an excellent illustration of consequent problems, including damage to infrastructure and an accompanying need for continuous and expensive maintenance works; a deficit in sediment delivery to the coast and associated beach retreat; water table lowering with associated saline intrusion and damage to agriculture. Notwithstanding this series of problems, requests for permission to remove sediment continue to be submitted to the Basin Authority of Magra River (BAMR) and to other local agencies responsible for river management. Against this background, the BAMR has devised a new river management policy based on the comprehension and analysis of geomorphic processes. A research project has been undertaken with the aim of defining strategies for management of sediment and channel mobility. The approach is based on previous geomorphic knowledge and expertise, allowing incorporation of all available geomorphic data to support an audit of how the river works and deliver understanding of the long and short-term trends in bedload transport and channel geometry adjustment (Rhoads, 1994; Sear *et al*., 1995; Thorne *et al*., 1996; Newson *et al*., 1998; Kondolf *et al*., 2003). This methodology is, therefore, fully consistent with the fluvial system conceptual framework and assessment of recovery potential (Brierley and Fryirs, 2005; Brierley *et al*., 2008).

The objective of this paper is to illustrate the methodology used in the Magra River project to define a design strategy for promoting future sustainable management of sediment and channel processes at a catchment scale. The project was carried out with the aim of mitigating adverse physical impacts of previous policies on societal resources (infrastructure undermining, groundwater lowering, coastal retreat) by managing sediment resources over the longer term. Ecological damage and response to previous channel adjustments were not considered. In this paper, a sequence of steps will be considered: (i) hydro-geomorphic diagnosis, (ii) a summary of critical parameters sectorized at the network scale, (iii) definition of a strategy adapted to the geomorphic health and recovery potential of river segments. We particularly focus on how geomorphic analysis of channel changes and hydraulic sediment budgets can be used in combination for practical application to river management. Therefore, the paper starts by considering knowledge of past channel evolution and its causes, as they contribute to understanding the fluvial system and its contemporary condition. Then a more quantitative approach is used to investigate the sediment budget and the adjustment tendencies of the river. Finally, we describe how these analyses are combined using a multi-criteria approach, to define an overall plan for river management.

STUDY AREA

The Magra River catchment is located in Nothern Tuscany and Liguria (Central-Northern western Italy) (Figure 1), and has an area of about 1700 km^2. The general characteristics of the catchment are summarized in Table I. The physiography of the catchment is characterized by aligned ridges with a NW-SE trend, made up of Mesozoic and Tertiary units with folded structures, separated by two main basins with a similar trend: to the west is the valley of the Vara River, the main tributary of Magra (catchment area of 572 km^2), and to the east is the middle-upper Magra valley (Raggi, 1985).

The area has a temperate climate with a summer dry season. The mean annual precipitation is 1707 mm, reaching a maximum of approximately 3000 mm in the upper part of the Magra basin. The mean daily discharge, mean of the maximum annual daily discharges (maximum annual peak discharges were not available), and the largest recorded flood discharge recorded at the two gauging stations with the longest record in the basin (45 years and 39 years for the Magra and Vara, respectively) are reported in Table I. The Magra gauging station is located on the middle-lower Magra (upstream the Vara confluence) and the Vara station is located on the middle Vara (Figure 1).

The Magra River has a total length of about 70 km, while the Vara River, the Magra's main tributary, has a length of about 58 km. The two river courses were initially classified into a series of relatively homogeneous reaches and sub-reaches (Figure 1). A first division into 10 main segments (MA, MB, MC, MD, ME, VA, VB, VC, VD, VE) reflects the major structural controls (direction and confinement of the alluvial valley floor), while a second division into sub-units (MA, MB1, MB2, . . ., ME1, ME2, etc.) was mainly based on channel morphology, resulting in a total of nine and seven sub-reaches for the Magra and Vara, respectively. Channel morphology is predominantly wandering in the unconfined reaches (MB, MD2-ME1, VE), sinuous with bars along the semi-confined reaches (MA, MC, MD1, VA, VB, VC, VD), and sinuous along the terminal reach of the Magra River (ME2). Channel

DOI: 10.1002/rra

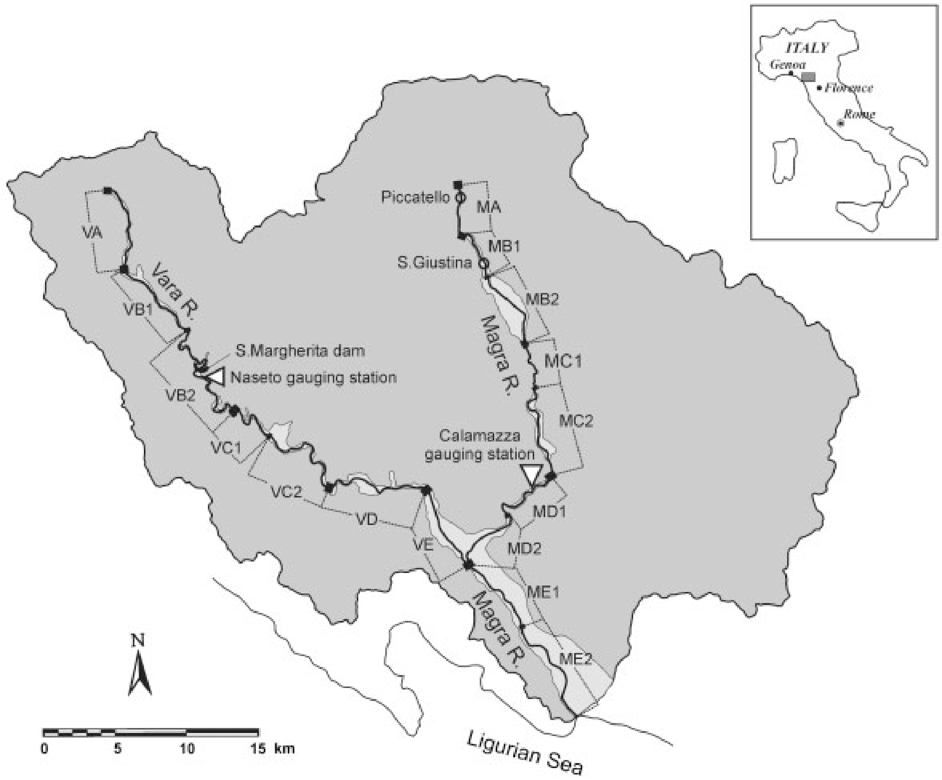

Figure 1. The Magra River catchment showing the sub-division of the two rivers into relatively homogeneous geomorphic reaches. Piccatello and Giustina are the two sections for which some bedload measurements are available

gradients range from 0.01 (MA) to 0.0004 (ME2) along the Magra River, and from 0.013 (VA) to 0.0037 (VE) along the Vara River The median particle diameter (D_{50}) varies between approximately 17 and 91 mm along the Magra River, and between 12 and 68 mm along the Vara River (Rinaldi *et al*., 2008). Riverbanks are predominantly non cohesive (i.e. composed of coarse gravel) in the middle-upper reaches, and composite (i.e. composed of a basal layer of gravel and an upper layer of more cohesive sediments) along the lower reaches.

Human impacts during the period of investigation on the Magra catchment and on the main river channels can be summarized as follows: (1) reforestation in the drainage basin (since 1920s–1930s); (2) construction of levees, groynes and other bank protection structures, concentrated along the lower parts of the Magra and Vara rivers (since 1920s); (3) construction of a dam in the middle Vara (1930s), and of a smaller dam (1950s) in the upper Magra catchment; (4) intensive sediment mining (1960s–1980s). This last pressure has certainly had the most impact, with a period of intense activity approximately between 1960s and 1980s, particularly along the lower reaches of Vara (VE) and Magra (ME). The quantity of sediment extracted from the lower reaches has been estimated to be

Table I. Physiographic and hydrological characteristics of the study rivers

River	Drainage basin area (km^2)	Length (km)	Basin relief (m)	Precipitation ($mm\,year^{-1}$)	Mean annual discharge ($m^3\,s^{-1}$)	Mean of maximum annual daily discharge ($m^3\,s^{-1}$)	Largest flood ($m^3\,s^{-1}$)
Magra	1699 (932*)	70	1639	1707	40	683	3480
Vara	572 (205*)	65	1603	1770	8.3	133.8	774

*Drainage area upstream of gauging stations where discharges are measured is in parentheses (first column).

DOI: 10.1002/rra

around 24 400 000 m^3 (Cavazza and Pregliasco, 1981) between 1958 and 1973 (i.e. about 1 600 000 m^3 $year^{-1}$), in comparison with an annual bedload transport estimated to be one or two orders of magnitude lower (see in the following sections).

CHANNEL CHANGES AND CAUSES

Data collection and methods

An extensive geomorphic study of channel changes was carried out on the two main alluvial branches (Magra and Vara Rivers) within the Magra catchment. This study included the collection and analysis of the following types of data and materials, as detailed in Table II: (1) historical maps; (2) aerial photos and topographic maps; (3) channel-bed longitudinal profiles; (4) field surveys.

The historical analysis commenced with an assessment of information from old maps (from the 16th to the 19th century) from archives and from previous studies (in particular Storti, 2000), which were useful to assess the channel morphology prior to the main human pressures, and to better understand the types and locations of human interventions. An archive of postcards and photos dating to the early part of the 20th century was also used to visually assess channel and hillslope conditions at some specific sites.

A systematic analysis of aerial photographs and topographic maps was then carried out using Geographic Information Systems (GIS). This incorporated the first topographic maps produced by the IGM (Istituto Geografico Militare), dating from 1877 with a scale of 1:50 000, and included a time sequence of aerial photographs at various scales (Table II). The GIS analysis included the georectification of the different images, digitizing of channel margins and measurement of the channel width. The 'active channel width', that is the width of the single low-flow channels plus that of unvegetated or sparsely vegetated bars, has been measured. Limitations and errors due to georectification and digitizing of channel morphological features have been described previously by several authors (e.g. Gurnell, 1997; Winterbottom, 2000; Hughes *et al*., 2006). We estimated maximum errors of 15–20 m and 5–6 m for our measurements based on map and aerial photograph sources, respectively. A systematic quantitative analysis of changes in active channel width concentrated on alluvial reaches that were not significantly constricted by hillslopes and were, therefore, relatively free to adjust their dimensions (MB, MD2-ME1, VC2-VD, VE). Reaches with fixed artificial banks or those that were excessively controlled by human constrictions (in particular the sub-reach ME2) were not included in this analysis. However, mapping of the river courses in all reaches was incorporated in the application of the Erodible Corridor Concept (see the following sections).

A complete set of channel cross-sections was available from a survey undertaken during 1989 along the entire length of both study branches, while a time series of channel-bed longitudinal profiles (from 1914 to 2000) was available only for the lower reaches of Magra (MD, ME) and Vara (VE), limiting reconstruction of bed-elevation trends to these reaches.

An extensive geomorphic field survey was carried out between 2003 and 2006 along all the study rivers. This involved the use of standardized forms specifically designed to record channel characteristics and changes (Rinaldi, 2008). The field surveys were useful to extend interpretations of past bed-elevation changes and present trends of vertical adjustments, based on a range of types of field evidence (e.g. differences in elevation between geomorphic surfaces, sedimentary features, vegetational evidence, etc.), on those reaches where topographical data were not

Table II. Summary of data sources used for the analysis of channel changes

Historical maps (scale)	1823 (1:50 000), 1852 (1:50 000), 1877 (1:50 000) VE: 1908 (1:25 000)
Aerial photos and topographic maps (scale)	1937/38 (1:18 000), 1954 (1:66 000), 1971 (1:66 000), 1981 (1:66 000), 1992 (1:66 000), 1995 (1:40 000), 1999 (1:40 000), 2003/04 (1:33 000), MB, MD, ME: 2006 (1:8 000)
Topographic surveys (longitudinal profiles)	MB: 1989, 2006, MD-ME: 1914, 1958, 1971, 1989, 1999/2000, 2006, VD-VE: 1958, 1971, 1989, 1999/2000
Field surveys	2003/06

DOI: 10.1002/rra

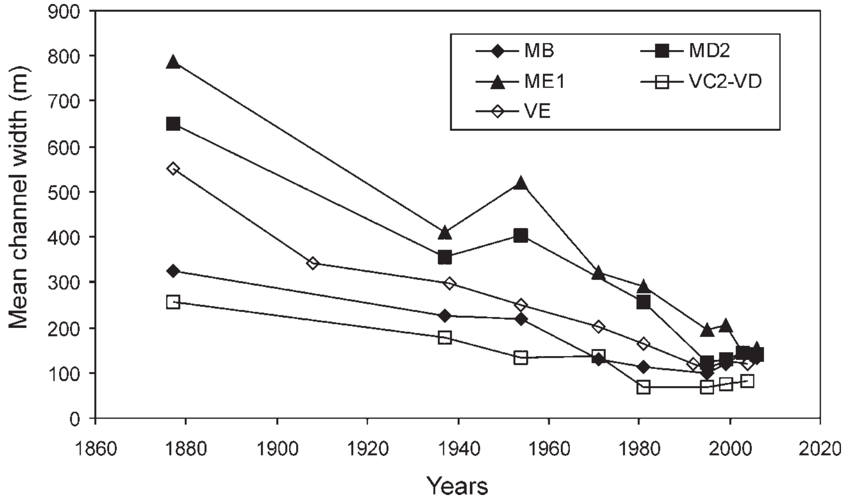

Figure 2. Changes in active channel width (i.e. low flow channel and unvegetated bars) from 1877 to 2006 along selected alluvial reaches of the Magra River (MB, MD2, ME1) and the Vara River (VC2-VD, VE), which have no significant lateral constrictions

available. This allowed classification of vertical changes for all the study reaches, which contributed to the subsequent definition of sediment management strategies. During the field surveys in 2006, a topographic thalweg profile was also surveyed along reaches MB and MD2-ME1.

Results and discussion

Analysis of channel changes along the main (Magra and Vara) alluvial branches provided a detailed reconstruction of the temporal trends in active channel width (Figure 2). This analysis shows a progressive reduction of active channel width through time, from the first available measurements in 1877 until 1995, when channel width reached a minimum in all investigated reaches. Along the Magra reaches, notably MD2 and ME1, a local peak in width is observed in 1954 in comparison with 1937. This is probably related to a large number of days with relatively high discharges during 1951 and 1952, as revealed by analysis of flow records from the Calamazza gauging station. A change in the channel pattern over time was also observed within most reaches, with a transformation from an originally braided morphology (particularly along the MB and the lower reaches MD2, ME1, VE) to a predominantly single-thread or transitional (wandering) morphology.

Mirroring the results of studies of other rivers in central-northern Italy (Rinaldi *et al*., 2008; Surian *et al*., 2009b), three different phases of adjustment can be identified based on the type of adjustment and also its rate (Table III). A first phase of channel narrowing can be observed, in most cases between 1877 and 1954, although this phase extended until 1971 in reach VC2–VD on the Vara branch. This first phase results from land use changes at the basin scale: construction of check-dams along tributaries, and construction of groynes along the downstream reaches of both the Magra and Vara. A second phase of major narrowing, which occurred between the 1950s and the beginning of the 1990s along other Italian rivers in relation to the additional effect of intensive sediment mining (Surian *et al*., 2009b), is not clearly observed in this catchment. Instead, channel narrowing continued at a similar rate to that observed during the first period in the Magra study area.

A phase of partial channel width recovery can be recognized after 1995, although this widening phase is not as strongly observed across other Italian rivers as the first two phases (Rinaldi *et al*., 2008; Surian *et al*., 2009b). For the Magra and Vara, however, this phase of widening appears to be quite clear, and it can be explained by renewed sediment supply and mobility lasting recent years, promoted by a series of flood events (particularly those of 1999 and 2000) coupled with a (delayed) response to the cessation of the intensive sediment exploitation of the previous decades. This trend of recent widening associated with more intense floods during the 1990s has also been observed along French rivers draining from the Alps, notably on the lower Ain River (Rollet, 2007) and also the Drôme (Liébault, 2003) following floods in 1994.

DOI: 10.1002/rra

Table III. Summary of changes in active channel width for each of three phases of channel evolution

River reach	Phase I				Phase II				Phase III			
	*T*1	Δw (m)	$\Delta w/(w_{max}-w_{min})$ (%)	Δw/*T* (m year^{-1})	*T*2	Δw (m)	$\Delta w/(w_{max}-w_{min})$ (%)	Δw/*T* (m year^{-1})	*T*3	Δw (m)	$\Delta w/(w_{max}-w_{min})$ (%)	Δw/*T* (m year^{-1})
MB	1877–1954	−105.9	−47	−1.37	1954–1995	−120.3	−53	−2.93	1995–2006	37.1	16	3.37
MD2	1877–1954	−246.9	−47	−3.21	1954–1995	−279.5	−53	−6.82	1995–2006	15.5	3	1.41
ME1	1877–1954	−268.5	−42	−3.49	1954–2003	−375.3	−58	−7.66	2003–2006	10.6	2	3.53
VC2-VD	1877–1971	−118.2	−62	−1.26	1971–1995	−70.9	−38	−2.95	1995–2004	13.3	7	1.48
VE	1877–1954	−301.0	−68	−3.91	1954–1995	−140.2	−32	−3.42	1995–2004	9.4	2	1.04

T1, T2 and T3 are the time intervals during which phases 1, 2 and 3 were, respectively, observed; Δw: width change over the entire phase; $\Delta w/(w_{max}\text{-}w_{min})$: ratio between width change observed during the particular phase of evolution and the difference between maximum and minimum width over the entire period for which data are analysed; Δw/*T*: annual rate of channel width adjustment during a phase of evolution.

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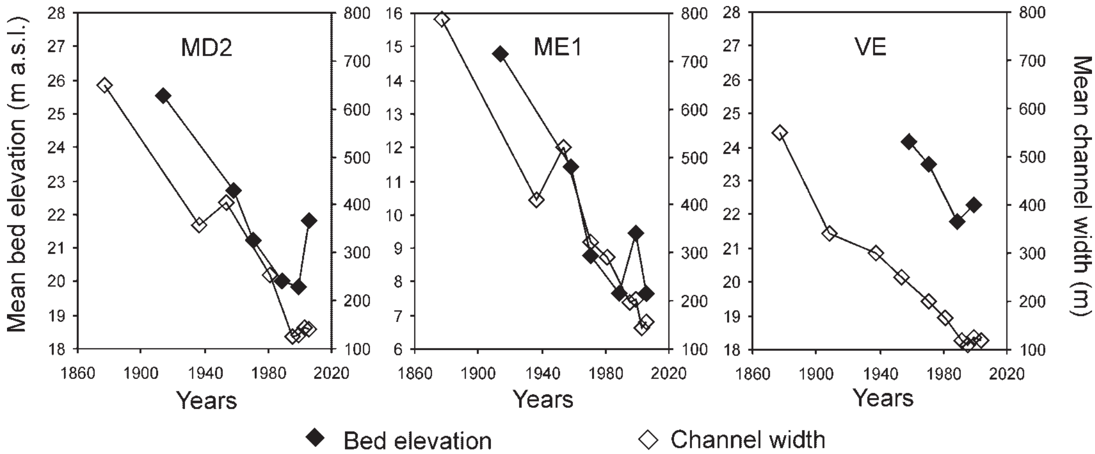

Figure 3. Changes in bed elevation and active channel width (reach mean values) through time along the lower Magra (MD2, ME1) and Vara (VE) reaches

A time series of longitudinal profiles for the lower reaches of the two study branches (VE, MD2, ME) permitted reconstruction of the degree and timing of bed elevation changes. Bed incision is the dominant type of vertical adjustment along these reaches, with bed-level lowering ranging from 2–4 m (approximately 0.05–0.1 m $year^{-1}$) (VE), to 5–8 m (approximately 0.05–0.09 m $year^{-1}$) (MD2-ME), with some localities along the lower Magra (ME2) showing changes as large as 10 m. Field evidence from other reaches of the two branches suggests that both rivers have incised along their entire course, but with a lower amplitude upstream.

For the reaches where longitudinal profiles are available, a comparison of bed-level adjustments with width adjustments through time provides an effective visualization of the temporal evolution of the lower Magra and Vara reaches (Figure 3). Similar bed-elevation changes are observed along reaches MD2 and ME1 between 1914 and 1989, and along the Vara River (VE) after 1958. During the last two decades, there has been a reversal in the direction of the previous trend for both bed elevation and channel width. Although slightly different patterns of changes are observed in different reaches, there is good correspondence between the reversal of temporal trends in channel width and bed elevation such that an increase in channel width is usually associated with a phase of aggradation, and *vice versa*.

A detailed discussion of the causes of these channel adjustments is beyond the scope of this paper, but all available information and data suggest that human impacts at both catchment and channel scales are responsible, as has been observed in studies of channel evolution on other Italian rivers (Rinaldi and Simon, 1998; Rinaldi, 2003; Surian and Rinaldi, 2003, 2004; Rinaldi *et al*., 2005; 2008; Surian *et al*., 2009b). Periodic oscillations and partial reversals of temporal trends can be related to of the occurrence of high magnitude floods or to periods within which there is a relatively high frequency of significant flow events.

Whatever the interpretation of the causes of channel adjustment, retrospective analysis of the channel geometry and hydrological series suggests three important issues for channel management: (i) the occurrence of major bed incision of the order of 8 to 10 m, which is unusually large in comparison with incisions reported from other countries (Surian and Rinaldi, 2003); (ii) a general trend of sediment deficiency throughout the 20th century and notably prior to the most intense mining activity (70s–80s), which resulted in channel degradation and narrowing; (iii) the ability of occasional flood events to slow down or reverse the general trend of narrowing and degradation, demonstrating that sediment sources are still available in the catchment.

QUANTIFICATION OF SEDIMENT TRANSPORT AND SEDIMENT BUDGET

Following the retrospective study, a second phase of diagnosis was conducted to assess the sediment transport and downstream delivery potential of the river channels, and to construct a sediment budget at the scale of the two study river branches. For each river sub-reach, a bedload histogram was obtained, using the procedure of Biedenharn *et al*. (2001). The flows during the period of record were divided into classes and the total bedload transported by

DOI: 10.1002/rra

each class was calculated by multiplying the frequency of occurrence of each flow class by the median bedload for that class. The detailed procedure was as follows:

(1) Discretization of channel reaches. The rivers were subdivided into relatively homogeneous hydraulic and hydrological sub-reaches. Commencing with the previously described geomorphic reach classification (Figure 1), a further sub-division of the Magra and Vara branches and also their main tributaries took account of variations in channel dimensions and hydrological discontinuities at major tributary confluences. This generated 11 (Magra), 12 (Vara) and 10 (tributaries) sub-reaches (Figure 4). The most downstream reach of the Magra River was excluded from this analysis because of the scarcity of gravel along the channel bed and its extreme artificiality in comparison with the other reaches as a result of the installation of numerous structures and heavy channel maintenance.

(2) Definition of the flow duration curve. Flow duration curves were estimated for all available discharge time series (three gauging stations on the Vara, two stations on the Magra, and two additional stations for two of the tributaries). Linear regression relationships were estimated between discharges at 30 different flow frequencies and drainage area (drainage area–flow duration curve method: Biedenharn *et al*., 2001), so that a flow duration curves could be estimated for any basin area.

(3) Cross-section and median diameter of bed sediments. Cross-sections surveyed in 1989 were used for this analysis. Although changes in channel geometry may have occurred since 1989, this was the only extensive topographic survey that was available (cross-section spacing every 200–250 m) and so it was used to represent the recent geometrical conditions of the two rivers. One cross-section was selected for each sub-reach to represent its geometry. Grain size measurements were performed in two main periods: (a) during summer 2004, 27 measurements were obtained along the Magra and Vara and 10 measurements along the main tributaries using the pebble count method on bar surfaces; (b) during 2005–2006, 13 volumetric samples were collected and analysed to provide a better characterization of the sub-surface layer for application of bedload formulae (Bunte and Abt, 2001).

(4) Calculation of flow rating curves using 1-D hydraulic modelling. Hydraulic modelling was performed using HEC-RAS 3.1.1 software (Hydrologic Engineering Center, 2003), to calculate the water level elevation profiles for a series of discharges and so define the flow rating curve and the other associated hydraulic parameters necessary for bedload calculation at each of the representative cross-sections.

(5) Calculation of the mean annual bedload capacity. The following bedload formulae were selected as being best suited to the channel characteristics and bed material of the study rivers (Chang, 1988; Garde and Ranga Raju, 1985; Gomez and Church, 1989; Copeland *et al*., 1997): (a) Shields (1936); (b) Schoklitsch (1950); (c) Parker (1990); (d) Meyer-Peter and Müller, in the form corrected by Wong and Parker (2006). The bedload histogram was then reconstructed for each of the four equations by entering the mean discharge for each of the 30 classes of the flow duration curve into the bedload equations and then multiplying these bedload estimates by the frequency of occurrence of the discharge class. Total mean annual bedload for each sub-reach was then obtained by integrating the bedload histogram.

A series of indirect bedload measurements were available at two sections along the Magra River (Piccatello and S.Giustina, drainage areas, respectively, 77 and 159 km^2, Figure 1) from a previous study (Cooperativa Mediterranea Prospezioni, 2000), comprising measures of the volumes of sediment deposited in two trenches on the channel bed during a period of 1 year (March 1999–March 2000). During this period, 713 and 4319 m^3 of deposited sediment were measured, at Piccatello and Giustina in response to three and four flow events, respectively. Discharges associated with these events are not available, but the limited number of events suggests that the measurements are not particularly representative of the mean annual bedload, and so are used here only as an indication of the order of magnitude of the bedload in this upper part of the Magra River.

(6) Sediment budgets. Based on the sediment continuity equation (Chang, 1988; Garde and Ranga Raju, 1985), a mean annual sediment budget was obtained for each sub-reach by the difference between the estimated input of bedload from the upstream sub-reach (assuming that its transport capacity is completely saturated), plus the estimated input from any major tributaries, and estimated output from the given sub-reach:

$$\Delta Q_{s(i)} = Q_{s\,\mathrm{IN}(i-1)} + Q_{s\,\mathrm{IN}(t)} - Q_{s\,\mathrm{OUT}(i)} \tag{1}$$

where $\Delta Q_{s\ (i)}$ = mean annual sediment budget (m^3 year^{-1}) for the sub-reach (i); $Q_{s\ \mathrm{IN}\ (i\text{-}1)}$ = mean annual sediment input (m^3 year^{-1}) from the upstream sub-reach (i-1); $Q_{s\ \mathrm{IN}\ (t)}$ = mean annual sediment input (m^3 year^{-1}) from tributaries in the sub-reach (i); $Q_{s\ \mathrm{OUT}\ (i)}$ = mean annual sediment output (m^3 year^{-1}) from the sub-reach (i).

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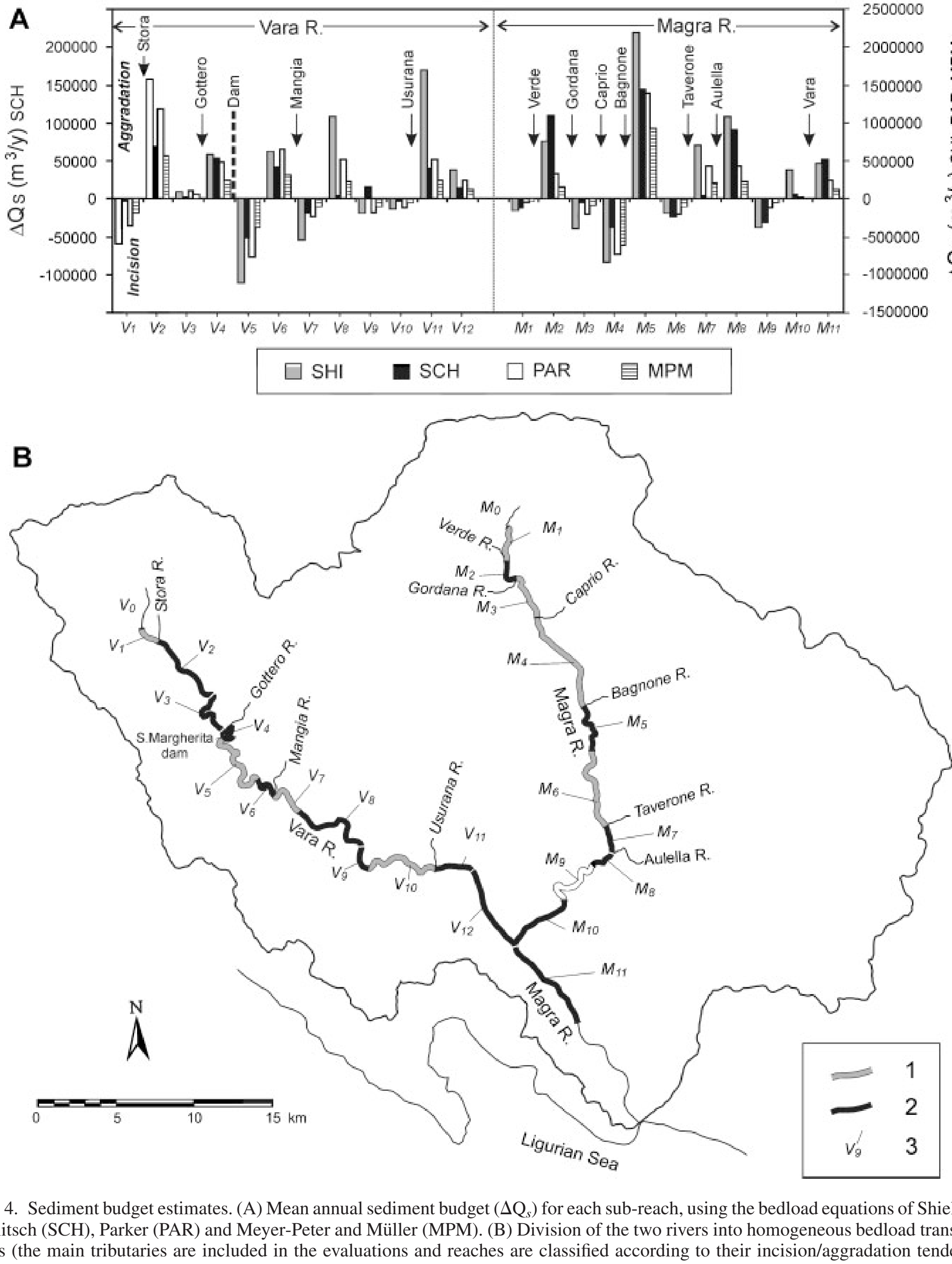

Figure 4. Sediment budget estimates. (A) Mean annual sediment budget (ΔQ_s) for each sub-reach, using the bedload equations of Shields (SHI), Schoklitsch (SCH), Parker (PAR) and Meyer-Peter and Müller (MPM). (B) Division of the two rivers into homogeneous bedload transport sub-reaches (the main tributaries are included in the evaluations and reaches are classified according to their incision/aggradation tendency). (1) Reaches with tendency to incision; (2) reaches with tendency to aggradation; (3) reach number

The estimated mean annual bedload sediment budgets are summarized in Figure 4. The mean annual sediment budget ΔQ_s ($m^3\,year^{-1}$) for a given sub-reach corresponds the excess or deficit of mean annual total volume of sediment, and represents the tendency of the sub-reach to aggrade (positive values) or degrade (negative values) given its hydraulic and sedimentary characteristics. The sediment budget for the most upstream (boundary) reaches

DOI: 10.1002/rra

of Magra and Vara (M_0 and V_0 respectively), and for the tributaries was assumed equal to 0 (corresponding to the assumption that all the transport capacity of the reach is saturated, i.e. the output of sediment is equal to the sediment volume entering into the reach). This is a reasonable assumption, and in agreement with field observations that revealed no evidences of significant incision or aggradation along these reaches.

Sediment budgets derived from the four bedload equations differed by one or two orders of magnitude (Figure 4A), but gave consistent results in relation to overall incision/aggradation tendencies for 22 out of 23 sub-reaches. The results obtained by the Schoklitsch equation appeared the most suitable for this case study, giving the closest, order of magnitude, estimates when compared with: (a) the available (although limited) measurements; (b) previous estimations performed by other authors on the same river (Cavazza and Pregliasco, 1981) and (c) other estimations of bedload and sediment yield of rivers with comparable characteristics and catchment sizes (e.g. Surian and Cisotto, 2007; Surian *et al*., 2009a).

A spatial pattern of the reaches with tendency for incision or aggradation can be identified (Figure 4B): (a) a prevailing tendency to incision in the middle-upper Magra, with a tendency to aggradation limited to some of the semi-confined sub-reaches (M_5, M_7, M_8); (b) a prevailing tendency to aggradation in the upper Vara (upstream of the dam), and alternating incision and aggradation along the middle course; (c) a tendency towards aggradation along the lower Vara (V_{11}, V_{12}) and Magra (M_{10}, M_{11}), due to a progressive reduction in sediment transport capacity attributable mainly to decreasing channel slopes.

Of course, these results are based on a series of assumptions and simplifications. For example, the 1989 cross-sections that were used could be associated with a previous phase of adjustment (i.e. incision and narrowing), while the bed material grain sizes, measured recently (2004–2006) and in aggrading reaches, could be finer than those present during a previous degrading phase. Therefore, the sediment budget results should be interpreted as representative of the general inclination of a reach for particular mean geomorphic, hydraulic and sedimentary characteristics, and are used here as a classificatory tool. Some contrasts with the actual geomorphic trend based on field observations should be expected and are discussed along with implications for sediment management in the next section.

MULTI-CRITERIA APPROACH TO DESIGNING A STRATEGY FOR SUSTAINABLE MANAGEMENT OF BED SEDIMENT

In this last phase, the procedures and methodologies developed for the BAMR to obtain an overall design strategy promoting sustainable sediment management, based on the integration of all the knowledge obtained during the diagnosis phases, are described. Four main aspects are considered: (1) synthesis step: simplification of diagnosis data to establish a single indicator of geomorphic health; (2) strategic step: proposed actions based on the previous synthesis; (3) a practical methodology to promote sediment delivery based on the definition of the 'functional mobility corridor' (FMC) or Erodible Corridor Concept (ECC) concept, and to identify suitable areas for potential sediment recharge to promote active restoration of sediment transport; and (4) a communication strategy for sediment management at the catchment scale based on using a map.

Simplification of existing data to establish a single indicator of physical health

In the context of channel sediment management, we have attempted to integrate different relevant aspects and information deriving from retrospective analysis and bedload quantification. As described previously, both rivers are incised due to a series of human impacts and disturbances, but during recent decades a reversal of this tendency is often observed. The present trend of bed-level adjustment (incising or aggrading) represents the most obvious information needed for sediment management purposes, but it is also important to compare this tendency and attempt to classify the present degree of recovery to overall bed-level changes in the longer term. In an attempt to account for all these aspects, four preliminary indicators were used to summarize the diagnosis information (Table IV):

(1) Secular bed-level changes (at the scale of about 100 years, i.e. from 1900 to 2006). Five classes of bed-level changes were defined, from relatively stable (not significant changes) to very intense incision. Situations of net aggradation at this temporal scale were never observed along the study rivers, therefore this case was not included in the classification.

DOI: 10.1002/rra

Table IV. Summary of bed-level changes and trends based on four complementary classifications and established for each of the reaches

Bed-level changes (from 1900 to 2006)	Present trends (last 17 years)	Bed-level recovery compared to 1950	Hydraulic sediment budget
(*S*) relatively stable (changes ranging from 0.5 to −0.5 m)	(*A*) aggrading	(*A*) recovery >100% (i.e. net aggradation compared to 1950)	(*A*) aggrading ($\Delta Q_s/Lw > 15 \times 10^{-2}$ m year^{-1})
(*Il*) limited incision (from −0.5 to −1 m)	(*S/A*) stable/ aggrading	(*B*) recovery from 80 to 100%	(*S/A*) stable/aggrading ($0 < \Delta Q_s/Lw \leq 15 \times 10^{-2}$ m year^{-1})
(*Im*) moderate incision (from −1 to −2 m)	(*S*) stable (dynamic equilibrium)	(*C*) recovery from 50 to 80%	(*S*) stable ($\Delta Q_s/Lw = 0$ m year^{-1})
(*Ii*) intense incision (from −2 to −4 m)	(*I*) incising	(*D*) recovery from 0 to 50%	(*S/I*) stable/incising (-15×10^{-2} m year^{-1} $\leq \Delta Q_s/Lw < 0$)
(*Iii*) very intense incision (<−4 m).		(*E*) recovery <0% (i.e. still incising)	(*I*) incising ($\Delta Q_s/Lw < -15 \times 10^{-2}$ m year^{-1})

(2) Decennial trend of bed-level adjustments. While it is important to know channel changes at a temporal scale of the order of 100 years, to define present trends of adjustments (incising, aggrading) or geomorphological stability (dynamic equilibrium) it is more appropriate to refer to a time scale of the order of the last decade (Shields *et al*., 2003). In our study, we referred to data from the last 17 years (from 1989 to 2006) and field evidences collected during the geomorphic surveys (2003–2006). Four classes of present trends of bed adjustments were defined (Table IV), with an intermediate class (stable/aggrading) indicating frequent situations where there was evidence of aggradation and relative stability (dynamic equilibrium) along the same reach.
(3) Bed-level recovery since 1950. For the purpose of channel management, it was important to classify the degree of bed-level recovery of river reaches with respect to their condition in 1950, although the quantification of bed-level changes since 1950 was difficult, and some gross simplification was necessary. The year 1950 was selected because it represents a turning point between an early 20th century river full of sediment and a late 20th century river with a significant sediment deficit inducing a number of problems. More detailed arguments justifying the choice of this date as well as for other aspects of the definition of the 'FMC' are developed below. For the reaches where a long time-series of longitudinal profiles was available, bed-level changes after 1950 were estimated by interpolating between the existing data. For the remaining reaches, we assumed the same percentage of total changes (1900–2006) occurred after 1950 as the average for adjacent reaches where data were available.
(4) Hydraulic sediment budget. We used the sediment budget as an indicator of the tendency of a reach towards incision or aggradation. Reaches with a sediment budget exactly equal to 0 (stable or in equilibrium) are restricted to the extreme headwaters of the Magra and Vara, and to the tributaries, where this condition was assumed (as explained previously). In order to define other situations that were not perfectly in balance but showed a very limited tendency to incision or aggradation, we defined two classes of small changes (close to equilibrium) and two other classes with a more substantial tendency to sediment excess or deficit. These distinctions were based on the mean annual sediment budget per unit length and per unit width ($\Delta Q_s/Lw$) obtained using the Schoklitsch bedload equation.

Finally, from the combination of all possible cases of the above four basic indicators, we defined a six-class geomorphic health index (Table V). We used three macro-classes (1, 2 and 3) to which we assigned specific management actions (see next section). Class 1 includes cases of prevailing stability or limited incision (1900–2006), tendency to stability or aggradation, and high recovery. Class 3 includes prevailing conditions of moderate to intense incision (1900–2006), tendency to incision and low recovery. Class 2 includes situations with intermediate conditions between Classes 1 and 3. There is not always agreement between present trends determined by field evidences and by hydraulic calculations (Table V) and so situations with consistent estimates of tendencies to

DOI: 10.1002/rra

Table V. Significance of the geomorphic health index based on the classes deriving from the combination of the four previous codices aimed to sediment management (note that not all the possible combinations are included, as they are restricted to those actually observed)

Class	(1) Bed-level changes (from 1900 to 2006)	(2) Present trends (last 17 years)	(3) Bed-level recovery compared to 1950	(4) Hydraulic sediment budget
1A	*S*	*A, S/A*	*A*	*A, S/A, S*
1B	*S, Il*	*A, S/A, S*	*B*	*A, S/A, S*
2A	*S, Il*	*A, S/A, S*	*A, B*	*S/I, I*
		A, S/A, S	*C, D*	*S/I, I*
		I	*A, B*	*A, S/A*
		I	*C, D*	*A, S/A*
2B	*Im, Ii, Iii*	*A, S/A*	*B, C*	*A, S/A, S*
3A	*Im, Ii, Iii*	*A, S/A, S*	*C*	*S/I, I*
		S	*C*	*A, S/A*
		A, S/A	*D*	*A, S/A, E, S/I, I*
		A, S/A, S, I	*D*	*A, S/A, S*
3B	*Im, Ii, Iii*	*S, I*	*D, E*	*S/I, I*

aggradation or incision were ranked higher or lower, respectively, when compared with less consistent estimated tendencies.

Proposed actions based on the previous synthesis

From our analysis and diagnosis, it is apparent that a sediment deficit is the main problem in the Magra catchment, although some recovery is possible in the short-term in some of the reaches. As a result, management actions to improve the recovery process within reaches should aim to retain sediment in the channel network and induce natural sediment delivery at the reach scale from the floodplain storage (e.g. the encroached disconnected bars perched above the present active channel), or at the catchment scale from tributaries and connected hillslopes. Promoting natural recovery (i.e. self forming/self sustaining measures for sediment recovery such as allowing lateral channel mobility) should be prioritized over artificial interventions (i.e. artificial reintroduction of sediments by floodplain excavation or other sources), as the former strategy is less costly and more appropriate when the driving processes (sediment delivery and discharge regime) are still operating. Moreover, natural recovery processes are fundamental to the maintenance and evolution of physical habitats, and aquatic and riparian ecosystems (Boon *et al*., 1992; Piégay *et al*., 1994; Goodson *et al*., 2002; Shields *et al*., 2003; Palmer *et al*., 2005; Florsheim *et al*., 2008), and so such approach is more appropriate to the improvement of ecological status (Habersack and Piégay, 2008) and is also less expensive than artificial interventions.

Management actions to promote sediment recovery at the scale of the main alluvial channels (Magra and Vara) include: (*M1*) move sediments trapped upstream of weirs; (*M2*) move instream sediments; (*M3*) move sediments accumulated on the floodplain into the channel; (*M4*) carry out a bedload release downstream of dams; (*M5*) move sediments in situations of hydraulic risk (for aggradation); (*M6*) introduce sediments deriving from other reaches; (*M7*) introduce sediments in situations of risk (for local scour). These actions can be associated with the three main macro-classes of the river classification (Table VI), and a series of associated guidelines for sediment management have been defined (Rinaldi, 2007). Finally, reaches where the FMC can be encouraged to promote additional sediment supply from eroding banks were identified as reaches with wider valley floors and a natural tendency to lateral mobility, that were predominantly incised with low bed recovery (class 3) or with longitudinal connection to the incised reaches.

Natural sediment recharge from catchment features were associated with the following actions: (*C*1) do not stabilize landslides; (*C*2) do not stabilize hillslopes in direct connection with the river channel network; (*C*3) do not stabilize eroding streambanks; (*C*4) do not build new transverse hydraulic structures; (*C*5) do not build new longitudinal hydraulic structures; (*C*6) avoid maintenance of existing hydraulic structures. These actions are not applicable in erosion or flood-risk sensitive reaches, such as urbanized areas or areas with particular high-risk elements (single buildings or infrastructure elements).

DOI: 10.1002/rra

Table VI. River classification and associated sediment management actions

Classes and associated channel bed conditions	Management actions
Class 1: Reaches with tendency to aggradation and high bed recovery compared to 1950	Promoting sediment shifting within the same reach (action *M2*) or to the closest downstream reach in class 3 (actions *M1* or *M5*)
Class 2: Reaches with variable tendencies and medium recovery	Allowing sediment extraction and shifting within the same reach (action *M2*) or to the closest downstream reach in class 3 (actions *M1* or *M5*)
Class 3: Incised reaches with low bed recovery compared to 1950	Not allowing any sediment extraction, except in case of local aggradation upstream of weirs (action *M5*), and promoting introduction of sediments deriving from upstream reaches in class 1 or 2 (actions *M6* or *M7*)

Practical methodologies to promote sediment delivery

Management of channel mobility. Traditional approaches used in the past for bank protection and managing channel mobility need to be increasingly reconsidered (Piégay *et al*., 2005) based on recognition and awareness of: (a) the economic costs of bank protection and its maintenance (Piégay *et al*., 1997); (b) the key role of bank erosion in channel dynamics and associated ecosystem services (Florsheim *et al*., 2008). These issues have led river managers to increasingly consider allowing rivers to migrate freely within a defined corridor, with property rights within the corridor usually being obtained either by negotiation with land owners or by buying the land outright.

The 'FMC' (Malavoi *et al*., 1998) (in italian: 'fascia di mobilità funzionale') or ECC (Piégay *et al*., 2005) was extensively applied in the Magra project, and will be adopted as the basis for future sustainable channel mobility management. The procedure was implemented within a GIS and included the following three steps (Figure 5): (1) overlaying the river courses during the last 50 years (1954–2004) to obtain the corridor of historical channel changes (CHCC, Figure 5A); (2) definition of the zones of possible future erosion (next 50 years) by calculating the

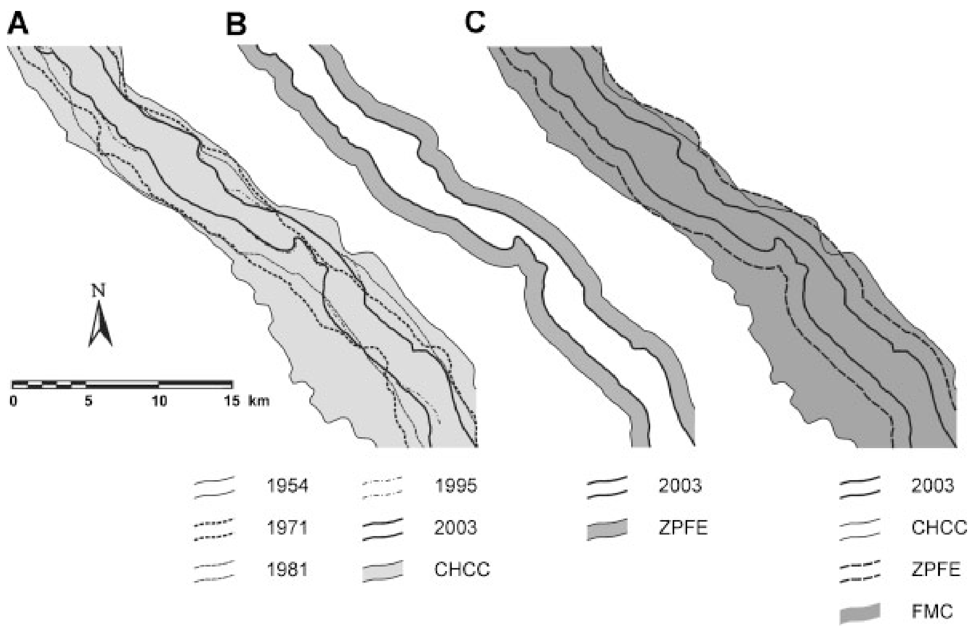

Figure 5. Application of the functional mobility corridor to the Magra River. (A) Delimitation of the corridor of historical channel changes (CHCC) as the external limit of channel courses during the last 50 years. (B) Delimitation of the zone of potential future erosion (ZPFE). (C) Delimitation of the functional mobility corridor as the external limit of CHCC and ZPFE

DOI: 10.1002/rra

present mean rates of bank erosion for a given sub-reach of the river, and then extrapolating this rate over a time interval of 50 years to generate two lateral strips of constant width for each sub-reach (ZPFE, Figure 5B); (3) overlaying and identifying the outer limit of the two previous zones (Figure 5C) to delimit the FMC. A further step is the definition of the 'Actual Functional Mobility Corridor', which reflects an on-going process of participatory management led by the BAMR and taking into account justified local constraints (e.g. main infrastructures, protection of drinking water wells, etc.), and in which decision-makers have to develop a specific land-use policy to permit erosion to occur.

In the above procedures, restriction of historical analysis to the previous 50 years, and the consideration of the next 50 years are motivated by the following reasons: (a) the rivers at the beginning of the 20th century showed abundant bedload, different channel patterns, wider beds and greater instability than they do today, implying that if pre-1950 data were also used, the erodible corridor would be overestimated because watershed and floodplain conditions prior to 1950 were very different from today; (b) such a wide erodible corridor, often occupying the entire valley floor, would have doubtful practical application, given that part of the alluvial plain is today urbanized; (c) regarding the zones of possible future erosion, 50 years has been selected as a suitable interval because it coincides with the life span of the management project.

Suitable areas for potential sediment recharge. In order to define an overall plan for sediment management at a catchment scale, some basic evaluation of potential recharge at the sub-catchment scale is necessary. For this, the coarse sediment fractions that are more suitable for recharge of bedload are of particular interest, rather than the fine sediment generated by soil erosion processes and transported into the fluvial system as wash load or suspended load. While there is a wide range of models to quantify sediment delivery deriving from soil erosion, methods for quantification of the production and delivery of coarse sediment transported as bedload are still lacking. Therefore, we used a semi-quantitative approach, similar to that recently applied to the catchment of the Drome River, France (Liébault *et al*., 2008), to obtain a classification of the basin areas with relative potential for sediment recharge. The method is based on the use of indices, quantified by assigning scores to parameters in proportion to their considered relative importance to this problem (full details of this methodology are reported in Rinaldi, 2007). Two types of sediment sources and relative indices were considered (Table VII): (A) *sediment recharge by landslides* (point sources); (B) *direct sediment recharge in the river network* (linear sources). In relation to the first index, the parameters considered to be most important were the landslide activity, the connection of the landslide to the fluvial network and the lithology, so that for each landslide the index was defined as the product $P_1 = \text{activity} \times \text{connection} \times \text{lithology}$. Similarly, for second index, some main physiographic and land use classes were defined, so that for each stem of the river network the index was defined as the product $P_2 = \text{lithology} \times \text{physiography/land use}$. For each index, five classes of potential of recharge (from very low to very high potential) were defined (Table VII).

Subsequently, to allow a classification and analysis at sub-catchment scale, a weighted average of each of the two indices ($P_{1\text{tot}}$ and $P_{2\text{tot}}$) was calculated, and five classes of potential recharge were defined by dividing the total range of values of each index in five arithmetic intervals (Table VII). A GIS analysis was carried out to visualize the results and identifying the sub-catchments of the basin with the highest potential of recharge by the two processes (landslides and direct recharge in the fluvial network). To select significant areas for potential sediment recharge from the first type of sediment source, only the landslides falling in the first two classes of the index P_1 (high and very high potential) were selected and excluding the landslides classified as at risk by the BAMR. A further selection of suitable landslides was based on the following additional factors: (a) distance of the source from the downstream incised reaches; (b) longitudinal connectivity of sediment to the incised reaches (i.e. the landslides upstream a dam located on the Vara River were excluded because the deriving sediment is not able to reach the incised reaches). To select significant areas for direct sediment recharge into the river network, the sub-catchments falling in the first two classes of the weighted average of the index $P_{2\text{tot}}$ were selected. A further selection was then based on the same parameters used for the potential recharge by landslides (distance and location, longitudinal connectivity).

In parallel to the GIS analysis, a series of field reconnaissance visits along the final reaches of the tributaries close to their confluence with the main river, classified the channel conditions in terms of sediment availability and to get some indirect information on the longitudinal sediment connectivity along the tributary. Information on the location and number of existing weirs was not available and it was not possible to perform a field census of them during this project, but a recording form was developed (Rinaldi, 2007), based on a series of indicators or evidence of

DOI: 10.1002/rra

Table VII. Definition of the indices and relative classes for the identification of suitable areas for potential sediment recharge

Sediment recharge by landslides

Activity	Connection	Lithology	P_1 = Activity × Connection × Lithology	Sub-catchment weighted average
1. Active = 2	1. Connected = 1	1. Very favourable = 3	1. Very high ($4 < P_1 \leq 6$)	$P_{1\text{tot}} = \frac{\sum_{i=1}^{n} P_1(i) \times A(i)}{A_{\text{tot}}}$
2. Dormant = 1	2. Disconnected = 0	2. Favourable = 2	2. High ($3 < P_1 \leq 4$)	1. Very high ($0.37 \leq P_{1\text{tot}} \leq 0.462$)
3. Inactive = 0		3. Intermediate = 1	3. Intermediate ($2 < P_1 \leq 3$)	2. High ($0.277 \leq P_{1\text{tot}} < 0.37$)
		4. Unfavourable = 0	4. Low ($1 < P_1 \leq 2$)	3. Intermediate ($0.185 \leq P_{1\text{tot}} < 0.277$)
			5. Very low ($0 \leq P_1 \leq 1$)	4. Low ($0.092 \leq P_{1\text{tot}} < 0.185$)
				5. Very low ($0 \leq P_{1\text{tot}} < 0.092$)

Direct recharge in the river network

Lithology	Physiography/Land use	P_2 = Lithology × Physiography/Land use	Sub-catchment weighted average
1. Very favourable = 3	1. Bare mountains = 2	1. Very high ($4 < P_2 \leq 6$)	$P_{2\text{tot}} = \frac{\sum_{i=1}^{n} P_2(i) \times L(i)}{L_{\text{tot}}}$
2. Favourable = 2	2. Vegetated mountains = 1.5	2. High ($3 < P_2 \leq 4$)	1. Very high ($2.14 \leq P_{2\text{tot}} \leq 2.58$)
3. Intermediate = 1	3. Vegetated hills = 1	3. Intermediate ($2 < P_2 \leq 3$)	2. High ($1.69 \leq P_{2\text{tot}} < 2.14$)
4. Unfavourable = 0	4. Plains and urbanised areas = 0	4. Low ($1 < P_2 \leq 2$)	3. Intermediate ($0.125 \leq P_{2\text{tot}} < 1.69$)
		5. Very low ($0 \leq P_2 \leq 1$)	4. Low ($0.80 \leq P_{2\text{tot}} < 0.125$)
			5. Very low ($0.36 \leq P_{2\text{tot}} < 0.80$)

DOI: 10.1002/rra

abundance or scarcity of sediment (such as presence, frequency and extension of channel bars, presence or absence of weirs or dams) from which tributaries classified as associated with scarcity of sediment were excluded from the final selection of suitable catchments for sediment recharge.

Mapping strategies for a sustainable management of bed sediment

The aspects of morphological evolution, sediment budget assessment, areas of potential sediment recharge, described above, were synthesized in a 'map of strategies for sediment management' at a scale of 1:60 000 (Rinaldi, 2007), which depicts river segments and associated sediment management recommendations, and identifies suitable areas for potential bedload recharge and associated management actions and/or measures at both network and catchment scales. Figure 6 presents a schematic representation of the main components of the original map. All the landslides and sub-catchments selected for potential sediment recharge, according to the previously described criteria, are reported on the map.

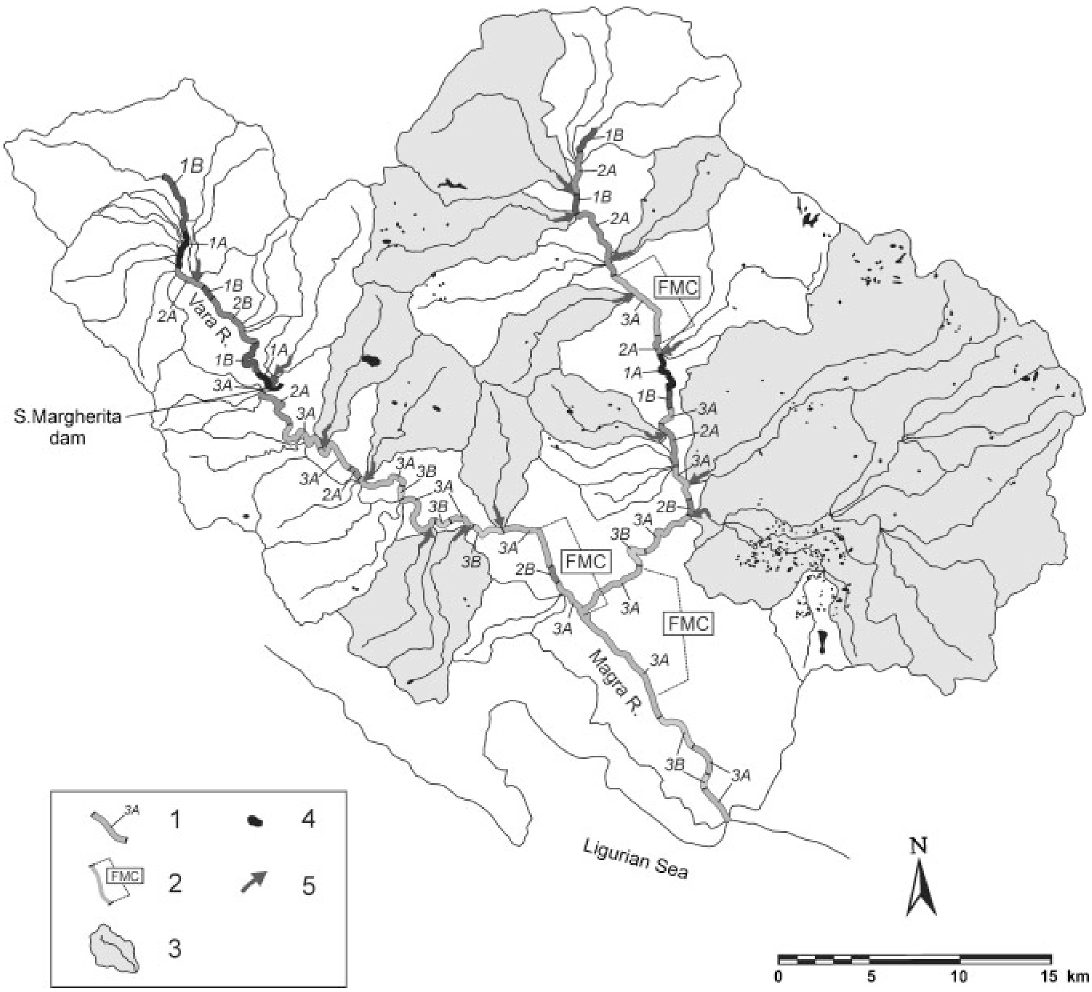

Figure 6. Schematic representation of the main elements included in the 'map of strategies for sediment management'. (1) Classification of the river segments based on the geomorphic health index. Codes from 1A to 3B (Table V), follow a grey scale from black, corresponding to class 1A, to light grey, corresponding to class 3B. Management actions (from M1 to M7) associated to the macro-classes 1, 2 and 3 are defined in Table VI. (2) Reaches where the Functional Mobility Corridor (FMC) can be promoted. (3) Sub-catchments selected for potential sediment recharge with associated actions from C1 to C6 (see text). (4) Landslides selected for potential sediment recharge with associated action C1 (see text). (5) Main tributaries with high sediment delivery

CONCLUSIONS

This paper has shown how a design strategy for promoting future sustainable management of sediment and channel processes has been defined for the Magra River catchment, by integrating geomorphic analyses of channel changes and trends, hydraulic sediment budgets and considerations of potential recharge at sub-catchment scale.

The Magra and Vara Rivers were severely affected by a combination of human impacts and disturbances, with sediment mining being the most important. Two main phases of channel adjustments were identified, similar to many other rivers in Italy, with a first phase of minor incision and channel narrowing occurring from about the end of 19th century to the second half of the 20th century, and a second phase of major adjustments (incision-narrowing) occurring between the 1950s and the early 1990s. During the last 15–20 years, a partial channel recovery (reversal of the previous trend in channel width and in some case of bed elevation) was observed in some reaches.

Knowledge of this channel evolution and its causes was used as a basis for defining channel and sediment management strategies, coupled with quantification of bedload transport and bed sediment budget, and the identification of areas most suitable for potential sediment recharge.

A 'map of strategies for sediment management' synthesises all the previous relevant knowledge and represents a scientific basis for future channel and sediment management, providing strategies for future management of sediments and associated delivering processes.

This paper focussed on alternative solutions to mitigate the adverse effects of hydraulic measures and to prevent any damage to infrastructure and properties in the medium term. Although ecological status was considered only from the literature, promoting solutions based on understanding natural processes and their self-restoration is unlikely to conflict with ecological status, but nevertheless, the proposed approach would benefit from ecological monitoring to confirm that such measures have benefits for riparian ecosystems and aquatic communities. An increase in habitat and species diversity similarly to the results provided by Austrian studies of channel widening and channel recovery (Muhar *et al*., 2008), may be anticipated.

ACKNOWLEDGEMENTS

This research was funded by the Autorità di Bacino Interregionale del Fiume Magra. The Secretary of the Basin Authority, F. Pittaluga, is particularly acknowledged for her support and continuous feedbacks. L. Solari is acknowledged for his support in quantification of sediment transport. G. Doretti is acknowledged for contributing to the research at various stages. F. Vannacci is acknowledged for grain size analyses. The staff and the PhD students S. Dufour, V. Gaertner, L. Grospretre, A. Honegger, J. Lejot, Y. Le Lay and A. J. Rollet of the hydrosystem research group of the University of Lyon/UMR 5600, L. Coppi, G. Doretti, S. Lamagna, L. Luppi, L. Bellacci and A. Vergaro of the Department of Civil and Environmental Engineering, University of Florence, and F. Comiti, L. Mao, E. Pecorari of the Department of Land and Agroforest Environments, University of Padova, are particularly thanked for their contribution during an intense week of reconnaissance and field measurements during the campaign of spring 2006. Finally, Walter Bertoldi and an anonymous referee are acknowledged for their constructive reviews.

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